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Seismic resistance estimation of existing turbogenerator foundation structures under ductility level earthquake impact by nonlinear static method

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Abstract. The article considers the multimodal nonlinear static method as a seismic resistance estimation method of existing turbogenerator foundation structures. The object of research is the turbogenerator foundation on the Tom-Usinsk State District Power Station. The article proposes a modified algorithm for the characteristic point search by the nonlinear static method. According to the calculations results, the existing foundation structures after a partial equipment replacement and the construction site increased seismicity are operational.

1. Introduction

Following the successful implementation of the Power delivery contract programme (DCP) aimed at the construction of new generating capacities in the Russian power industry, the Government developed a new DCP-2 programme under which the existing old capacities in a total volume of up to 41 GW are planned to be modernized.

During the first DCP programme about 15% of the total installed electric capacity in the Russian Federation was renewed. For the period from 2008 to 2017 about 4 trillion rubles were invested.

However, the anticipated growth in electricity demand since the beginning of the RAO UES reform did not materialize. Recession and slow recovery of the Russian economy in 2015–2018 did not generate the estimated 4.3% Compound annual growth rate in electricity demand resulting in a power surplus on the market. The peak load is 151 GW against the installed capacity of 243 GW.

Nevertheless, the Government decided to take advantage of the temporary surplus of capacity and renew old thermal power generating facilities since the modernized facilities need to be temporarily decommissioned. The programme DCP-mark, currently being DCP-2, was specially developed. Being actually analogous to the first DCP-1 programme, it is aimed at modernizing the oldest thermal power generating facilities (over 45 years old) in order to reduce operating costs and increase fuel efficiency. The service life of the renewed power plants has to be extended by 15–20 years.

The core of power plants of the 50–60s of the XX century is a steam- turbine plant. For the accurate operation of this type of machine, a frame foundation is required [4], [5], [7], [10] to meet both the requirements of strength and safe and trouble-free operation [3]. The frame foundation is a series of U-shaped frames rigidly embedded into the foundation slab and united by longitudinal beams (Figure 1).

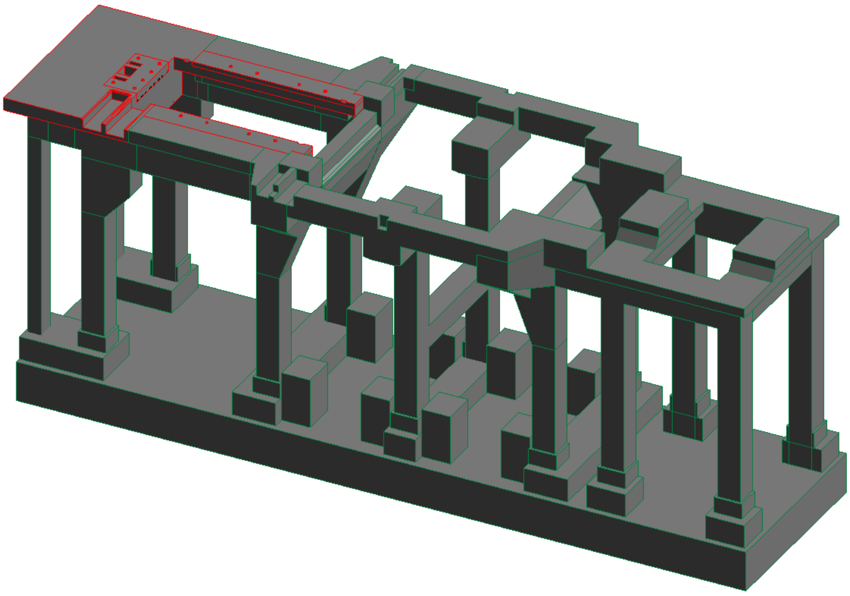


Figure 1. Frame foundation of the steam-turbine plant at the Tom-Usinsk State District Power Station

The space provided by the frames is necessary to accommodate the condenser. When upgrading the equipment, complete or partial replacement of the power plant and, when required, of the foundation structures is carried out. Over the past 70 years, regulations governing the design of building structures have undergone major changes. In particular, the seismic zoning plans [2] were refined, and modern equipment often enables to determine the seismicity of a construction site more accurately. During the reconstruction of power plants on the territory of Siberia, the background seismicity of a construction site changes increasingly due to microseismic zoning, and the foundations designed with a seismicity of 6 points on the MSK-64 scale require verification calculations for seismic impacts at a level of 7 points and higher on the MSK-64 scale.

The article presents seismic resistance assessment of existing turbogenerator foundation on the Tom-Usinsk State District Power Station when replacing the generator. Seismic impact analysis was performed using a multimodal nonlinear static method [14], [15], [16].

2. Methods for calculating higher mode of vibration

To determine the system response taking into account the influence of higher vibration modes we consider the following method and introduce the concept of a *modified inertial forces system*.

Modified inertial forces system means the system of forces obtained based on forces superposition by the method "Square Root of the Sum of Squares" [6], when the displacement of the top of the considered computational model corresponds to the total displacements obtained from linear spectral analysis. The graphic representation of inertial forces summation is shown in Figure 2.

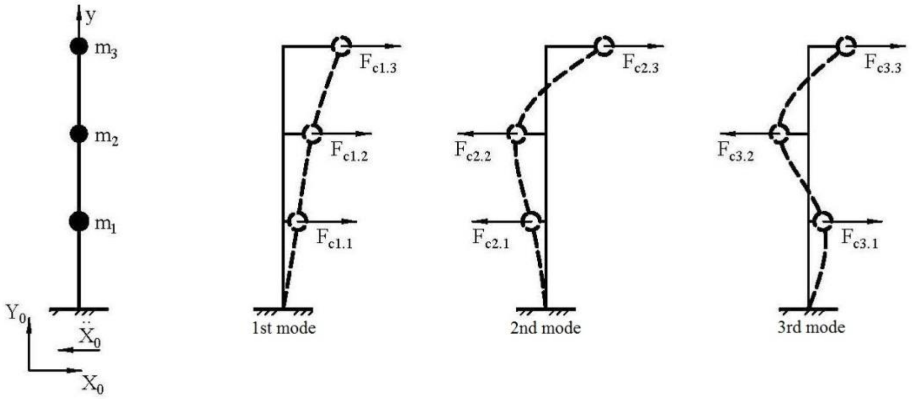


Figure 2. Graphic representation of modal response summation method "Square Root of the Sum of Squares"

Thus, the *modified inertial forces system* is determined by (1):

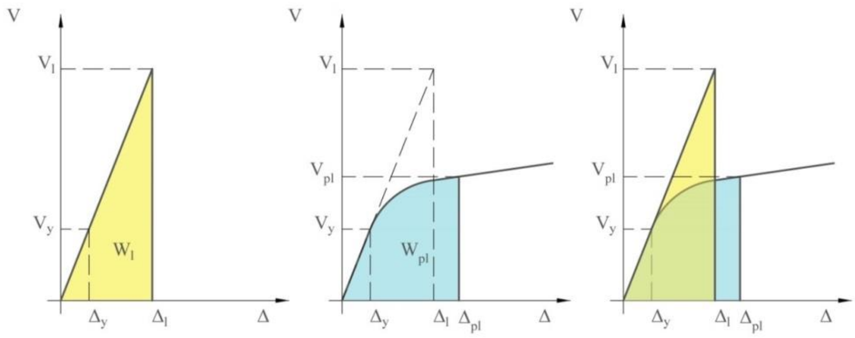
$$R_{sum} = \alpha\left(\sum_{i=1}^{n} R_i^2\right)^{\frac{1}{2}} \tag{1}$$

where R_i – modal structural response corresponding to the *i*-th form of natural vibrations;
$\alpha = {}^{\Delta_{RSA}}/_{\Delta_{SRSS}}$ – reduction ration equal to the ratio of maximum displacement of the top node of the system Δ_{RSA} obtained through response spectrum theory to displacements Δ_{SRSS}, obtained through modified forces system.

According to [8], [9], one needs to spend the same amount of energy to destroy a material regardless of the load applied (i.e, static slow, dynamic fast, single or multiple loading). Thus, the linear system deformation energy with an inertial forces modified system is identical to the system deformation energy allowing for plastic deformations. The target value of system energy capacity can be determined based on the modified inertial forces system (Figure. 3):

$$W_l = \frac{V_l \Delta_l}{2} \tag{2}$$

where V_l – shear force at the base of the system obtained through response spectrum analysis;
Δ_l – displacement of the top node of the system.



a) *б)* *в)*

Figure 3. Energy determination for elastic and elastic-plastic behaviour of a system with one degree of freedom: *a)* elastic behaviour; *b)* elastic-plastic behaviour; *c)* energy equality for elastic and elastic-plastic behaviour

The next stage in seismic resistance assessment is plotting the dependency graph "Shear force V – Displacement of the top node of the system Δ" – bearing capacity graph – based on a nonlinear static calculation method of a system with one degree of freedom under the action of a modified inertial forces system.

Given the energies of elastic and elastic-plastic deformation are equal, the obtained value of the top of the system displacement Δ_{pl} is the target value for assessing the seismic resistance of the entire system. This allows to determine inter-floor displacements, internal forces in the system elements as well as to analyze the inelastic behaviour of joints and system elements.

Depending on the position of the characteristic point on the bearing capacity curve, one can assess the general nature of the damage to the structure as a whole.

The object of research is existing turbogenerator foundation on the Tom-Usinsk State District Power Station. General characteristics of the steam-turbine plant are presented Table 1.

Table 1. Steam-turbine plant characteristics

№	Name	Value
1	Capacity, MW	*225*
.2	Voltage, V	*15750*
3	Nominal speed, r/min	*3000*
4	Critical speed I/II, r/min	*930 / 2590*
5	Mounting stator mass (with eye screws), kg	*175050*
6	Rotary mass, kg	*44900*
7	Bearing mass, kg	*5300*
g	End shield mass, kg	*3700*
9	Gas condenser mass, kg	*920*

The estimated seismicity of the construction site resulting from seismic microzoning is 7 points on the MSK-64 scale. The initial seismic action is given as a dynamic-response factor graph according to item 5.6 [2] (Figure 4).

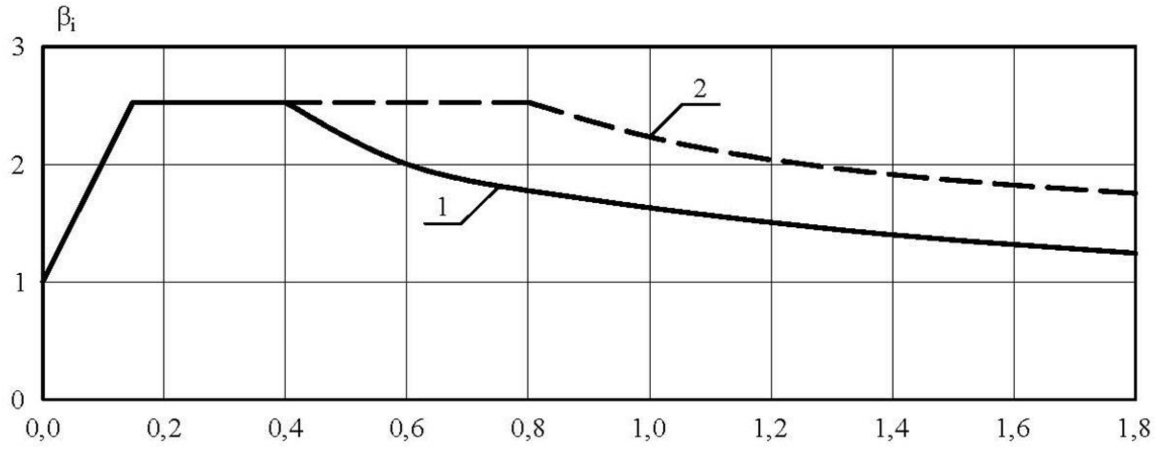


Figure 4. Dynamic-response factor graph

The material of the structures was adopted in accordance with the survey findings. The physical nonlinearity of the foundation elements is determined by the deformation diagrams of reinforcement steel and concrete are presented in Figures 5, 6.

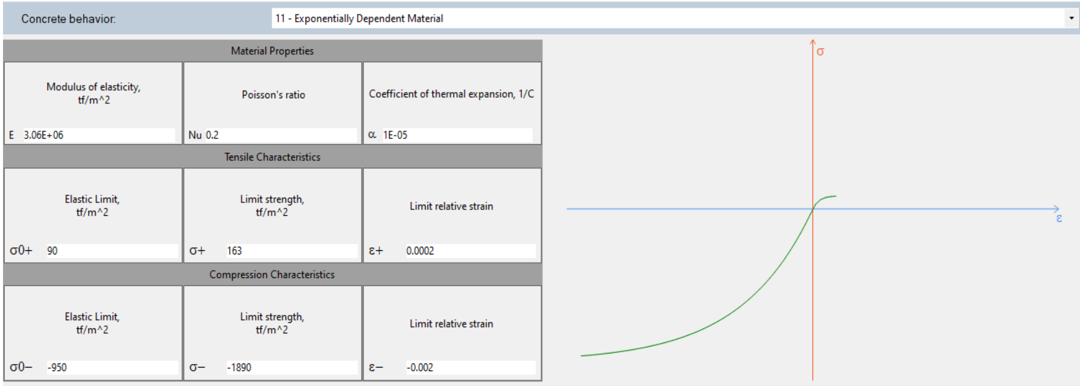


Figure 5. Deformation diagrams of concrete.

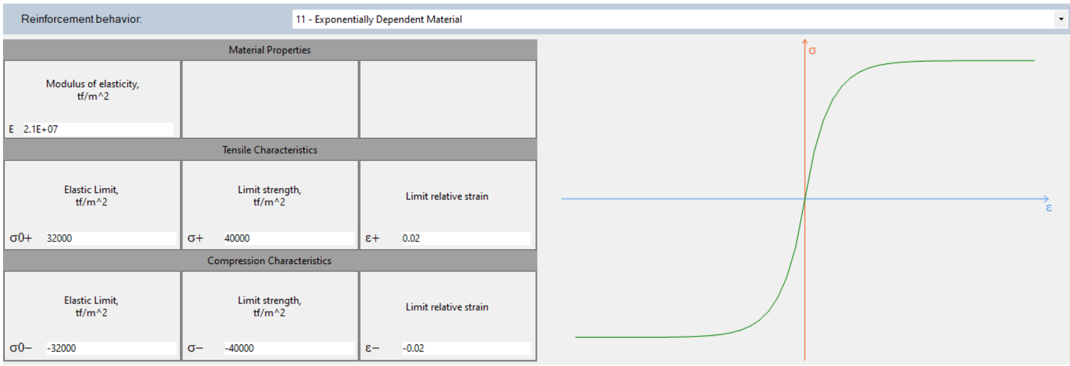


Figure 6. Deformation diagrams of reinforcement steel.

Linear elements of the design model (girders and columns) are modeled using physically and geometrically nonlinear finite elements of FE 410 rods; slab parts of the lower and upper structure of foundations are modeled using physically and geometrically nonlinear elements of the FE 442 shell. The joints of girders and columns are 3D finite elements with the use of rigid bodies. Figure 4 shows the general view of the design model.

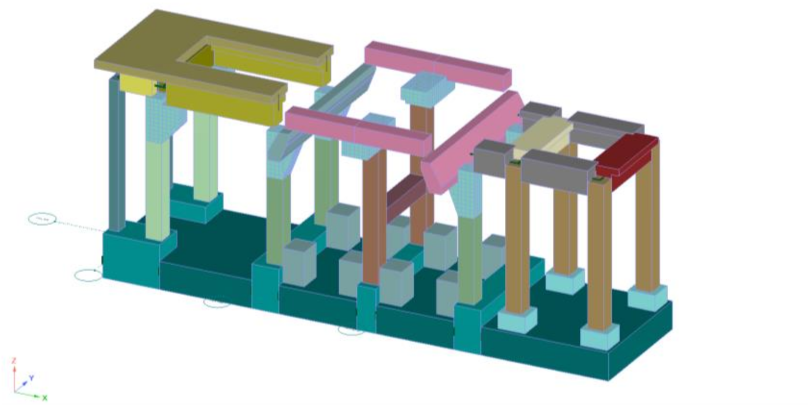


Figure 7. General view of the design model

The system of inertial forces for the multimodal nonlinear static method adopted is based on the modal system analysis [11], [12], [13]. The article presents the calculation data under seismic action along the axis of the steam turbine (along the X axis). Similar calculations were performed for seismic action transverse to the steam turbine axis (along the Y axis).

When analyzing modes of natural vibrations of turbine foundations, a form was found with a modal mass of more than 85% (Figure 8). When the modal mass of the main vibration mode is close to 90% of the total modal mass, no consideration of higher vibration modes is required as their influence on the overall system response is insignificant.

Thus, the distribution of forces corresponding to the main form of natural vibrations of the system is taken for the inertial forces system under the seismic action of the level “Ductility level earthquake”.

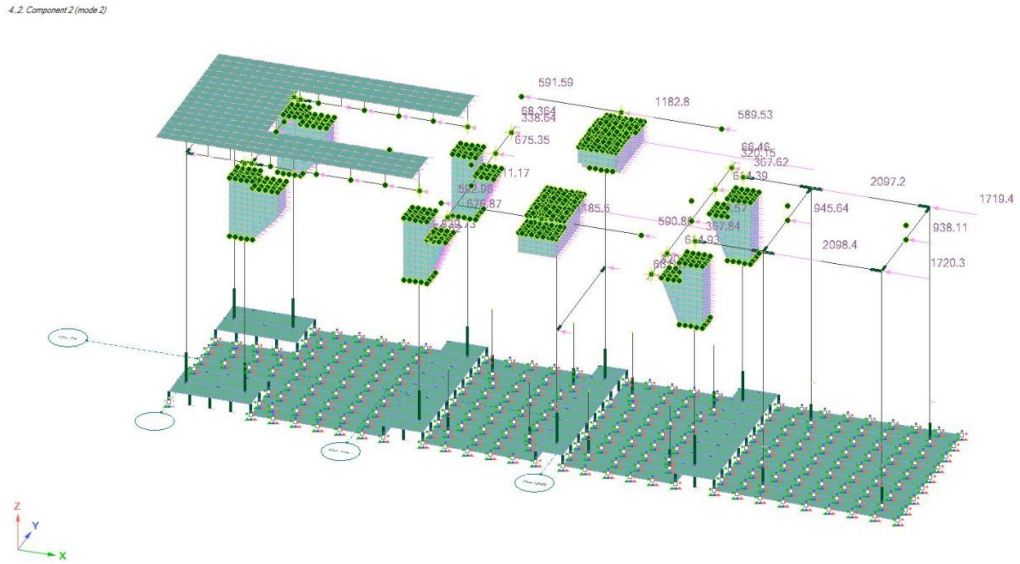


Figure 8. Inertial forces system for seismic assessment using nonlinear static method

3. Results

Based on the response spectrum theory and the Eq. (2), the following values were found:

- Maximum displacement of the top node of the system under the action of the modified system of forces is 6.80 mm;
- Shear force at the foundation base is 3496 kN;
- System energy capacity is 11.886 kJ.

To determine the most unfavorable response, a nonlinear static analysis was performed and a bearing capacity curve was plotted – a graph for dependency of displacements and shear forces at the base of the system. The characteristic point on the graph is that forming a figure under the curve with the area corresponding to the target value of the system energy capacity. The bearing capacity curve with the characteristic point is shown in Figure 9.

According to the location of the point on the bearing capacity curve, the following conclusions can be drawn:

- The existing turbogenerator foundation on the Tom-Usinsk State District Power Station is capable of accepting a seismic impact of 7 points on the MSK-64 scale;
- Deformations of the structure under seismic impact are elastic indicating significant bearing capacity reserve;
- Maximum displacement of the foundation top of accounts for 6.90 mm;

General view of the deformed model is presented in Figure 10.

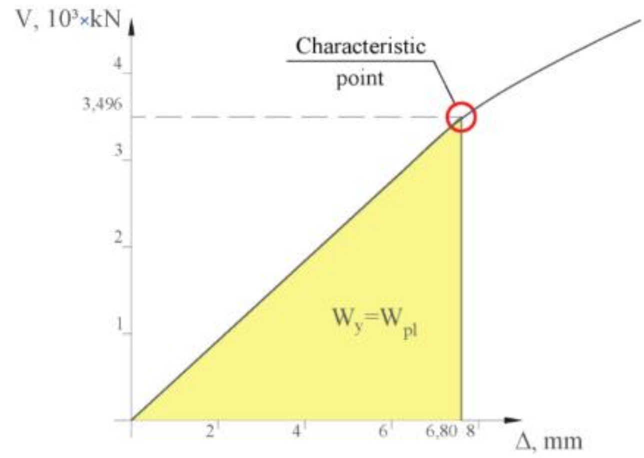


Figure 9. Bearing capacity curve

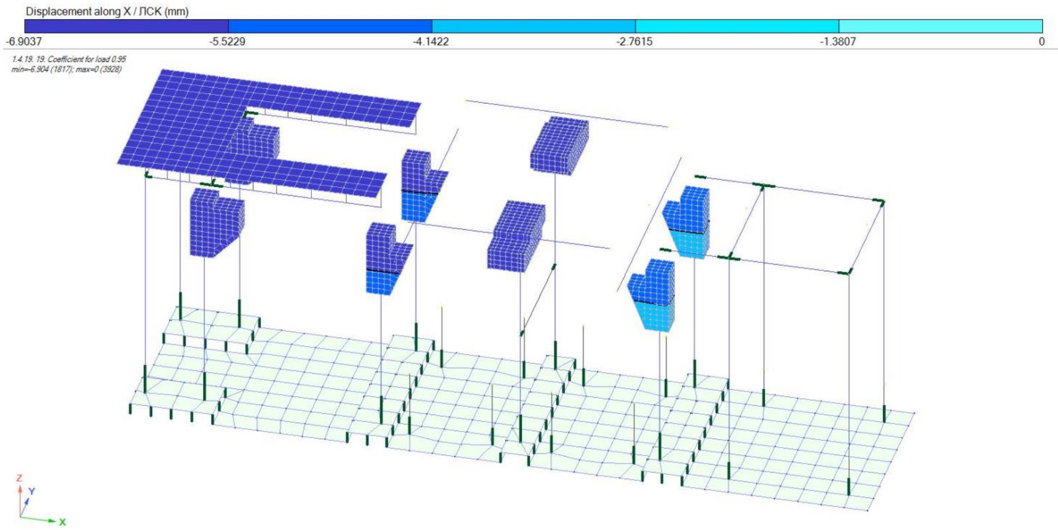


Figure 10. General view of the deformed model

4. Discussion

In the course of mathematical research, static and dynamic calculations were performed, a capacity curve for the design model of the foundation structures of a steam-turbine plant was plotted.

Based on the modal analysis, the sufficiency of taking into account only the main form of natural vibrations was determined, since its modal mass is close to 90%. The hypothesis of equal energies was used for further search for the characteristic point. Following the results of calculations, maximum displacements of the top of the system, internal forces and stresses in the elements, as well as the elastic nature of the overall response of the system were determined. In the course of the analysis, the authors used an algorithm allowing automating the nonlinear static method [1].

In addition, when analyzing the capacity curve, the maximum horizontal displacement accounting for 31.6 mm was determined under seismic impact at 9 points on the MSK-64 scale. Furthermore, the deformations of the foundation are elastic-plastic. Plastic deformations occur at the junctions of columns with foundations and girders.

It is worth noting that the used method is tolerant to the initial data in terms of seismic impact – it is sufficient to use the design spectrum [2], and with less computer time, the multimodal nonlinear static method can be a worthy alternative to the time history analysis.

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